

# Shape coexistence in Kr isotopes towards $N = 60$

*A Letter of Intent for SPES*

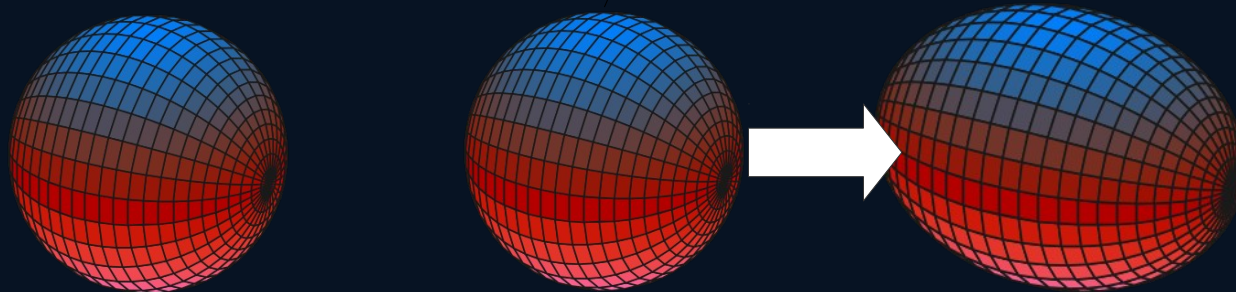
Victor Modamio LNL-INFN

# Shape evolution

Shell effects appear at  $N=60$  producing a striking quantum phase transition in Zr and Sr isotopes, besides the smooth increase of collectivity when going towards the mid-shell.

Mo92 0+ 14.84	Mo93 4.0E+3 y 5/2+ EC *	Mo94 0+ 9.25	Mo95 5/2+ 15.92	Mo96 0+ 16.68	Mo97 5/2+ 9.55	Mo98 0+ 24.13	Mo99 65.94 h 1/2+ β	Mo100 1.2E19 y 0+ β β <sub>9.63</sub>	Mo101 14.61 m 1/2+ β	Mo102 11.3 m 0+ β	Mo103 67.5 s (3/2+) β	Mo104 60 s 0+ β	Mo105 35.6 s (5/2-) β	Mo106 8.4 s 0+ β
Nb91 680 y 9/2+ *	Nb92 3.47E+7 y (7)+ *	Nb93 9/2+ *	Nb94 2.03E+4 y (6)+ *	Nb95 34.975 d 9/2+ *	Nb96 23.35 h 6+ *	Nb97 72.1 m 9/2+ *	Nb98 2.86 s 1+ *	Nb99 15.0 s 9/2+ *	Nb100 1.5 s 1+ *	Nb101 7.1 s + *	Nb102 1.3 s 1+ *	Nb103 1.5 s (5/2+) β	Nb104 4.8 s (1+) β <sub>n</sub> *	Nb105 2.95 s (5/2+) β
Zr90 0+ 51.45	Zr91 5/2+ 11.22	Zr92 0+ 17.15	Zr93 1.53E+6 y 5/2+ β	Zr94 0+ 17.38	Zr95 64.02 d 5/2+ β	Zr96 3.9E19 y 0+ β <sub>2.30</sub>	Zr97 16.91 h 1/2+ β	Zr98 30.7 s 0+ β	Zr99 2.1 s (1/2+) β	Zr100 7.1 s 0+ β	Zr101 2.1 s (1/2+) β	Zr102 2.9 s 0+ β	Zr103 1.3 s (5/2-) β	Zr104 1.2 s 0+ β
Y89 1/2- 100	Y90 64.10 h 2- *	Y91 58.51 d 1/2- *	Y92 3.54 h 2- *	Y93 10.18 h 1/2- *	Y94 18.7 m 2- *	Y95 10.3 m 1/2- *	Y96 5.34 s 0- *	Y97 3.75 s (1/2-) β <sub>n</sub> *	Y98 0.548 s (0-) β <sub>n</sub> *	Y99 1.470 s (5/2+) β <sub>n</sub> *	Y100 7.5 s (1-) β <sub>n</sub> *	Y101 448 ms (5/2+) β <sub>n</sub> *	Y102 0.36 s (5/2-) β <sub>n</sub> *	Y103 0.23 s (5/2+) β <sub>n</sub> *
Sr88 0+ 82.58	Sr89 50.53 d 5/2+ β	Sr90 28.78 y 0+ β	Sr91 9.63 h 5/2+ β	Sr92 2.71 h 0+ β	Sr93 7.423 m 5/2+ β	Sr94 75.3 s 0+ β	Sr95 23.90 s 1/2+ β	Sr96 1.07 s 0+ β	Sr97 426 ms 1/2+ β <sub>n</sub>	Sr98 0.653 s 0+ β <sub>n</sub>	Sr99 0.269 s 1/2+ β <sub>n</sub>	Sr100 202 ms 0+ β <sub>n</sub>	Sr101 118 ms (5/2) β <sub>n</sub>	Sr102 69 ms 0+ β <sub>n</sub>
Rb87 4.75E10 y 3/2- 27.838	Rb88 17.78 m 2- *	Rb89 15.15 m 3/2- *	Rb90 158 s 0- *	Rb91 58.4 s 3/2(-) β	Rb92 4.492 s 0- β <sub>n</sub>	Rb93 5.84 s 5/2- β <sub>n</sub>	Rb94 2.702 s 3(-) β <sub>n</sub>	Rb95 377.5 ms 5/2- β <sub>n</sub>	Rb96 0.199 s 2+ β <sub>n</sub>	Rb97 169.9 ms 3/2(+) β <sub>n</sub>	Rb98 114 ms (1,0) β <sub>n</sub> β <sub>2n...</sub> *	Rb99 50.3 ms (5/2+) β <sub>n</sub>	Rb100 51 ms β <sub>n</sub> β <sub>2n...</sub>	Rb101 32 ms β <sub>n</sub>
Kr86 0+ 17.3	Kr87 76.3 m 5/2+ β	Kr88 2.84 h 0+ β	Kr89 3.15 m (3/2+,5/2+) β	Kr90 32.32 s 0+ β	Kr91 8.57 s (5/2+) β <sub>n</sub>	Kr92 1.840 s 0+ β <sub>n</sub>	Kr93 1.286 s (1/2+) β <sub>n</sub>	Kr94 0.20 s 0+ β	Kr95 0.78 s 1/2 β	Kr96 0+ β	Kr97 β	62		64
Br85	Br86	Br87	Br88	Br89	Br90	Br91	Br92	Br93	Br94	60				

$N=50$

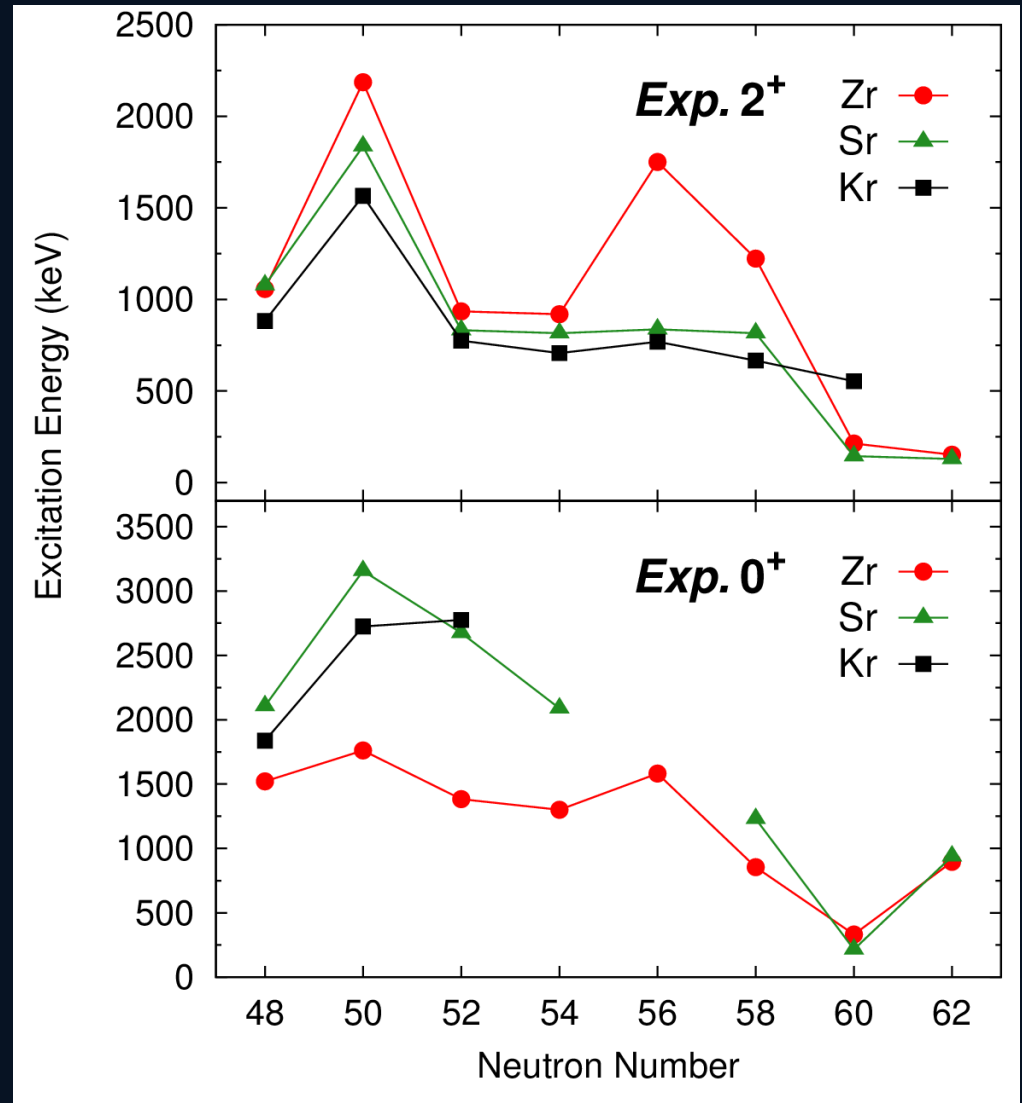


# Systematics

In  $^{100}\text{Zr}$  and  $^{98}\text{Sr}$  ( $N=60$ ) occur one of the most abrupt shape transition. From slightly spherical nuclei to highly deformed ones.

At the same time, different shapes coexist at almost degenerated excitation energies!!

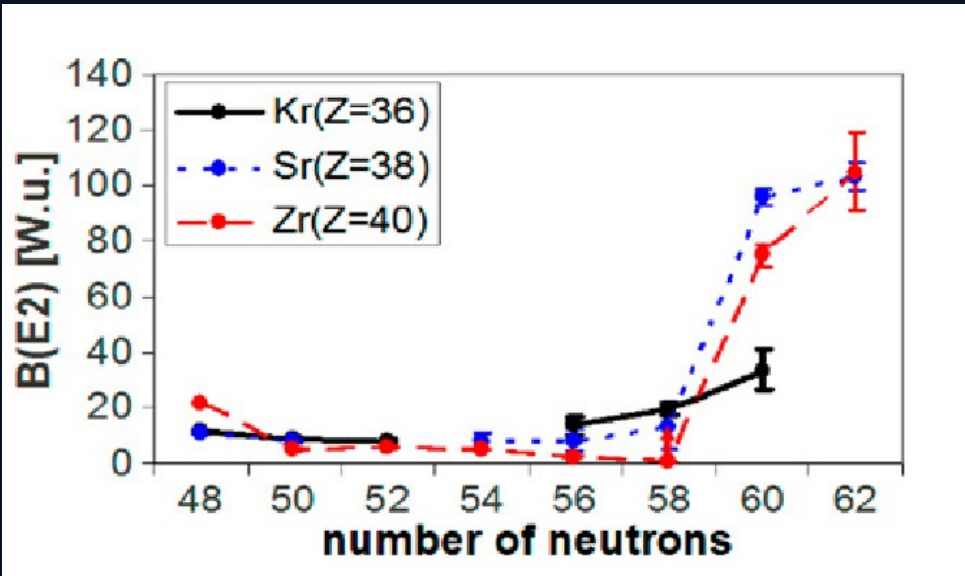
Is the shape coexistence playing an important role in the shape evolution in Zr, Sr and Kr isotopes?



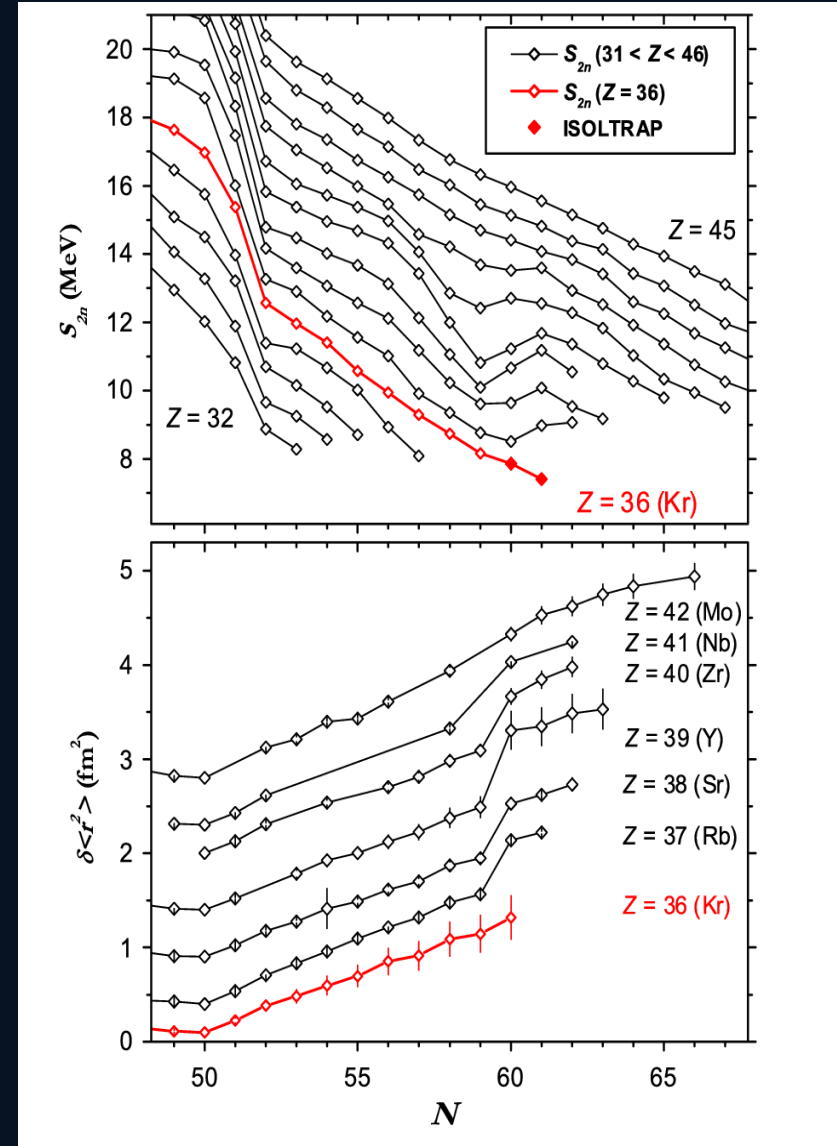
# Deformation in Kr

## Mass measurements and B(E2)

The Kr chain indeed, develops a very smooth transition to deformed (probably prolate) shapes.



Albers et al. NIM A 899, 1 (2013)



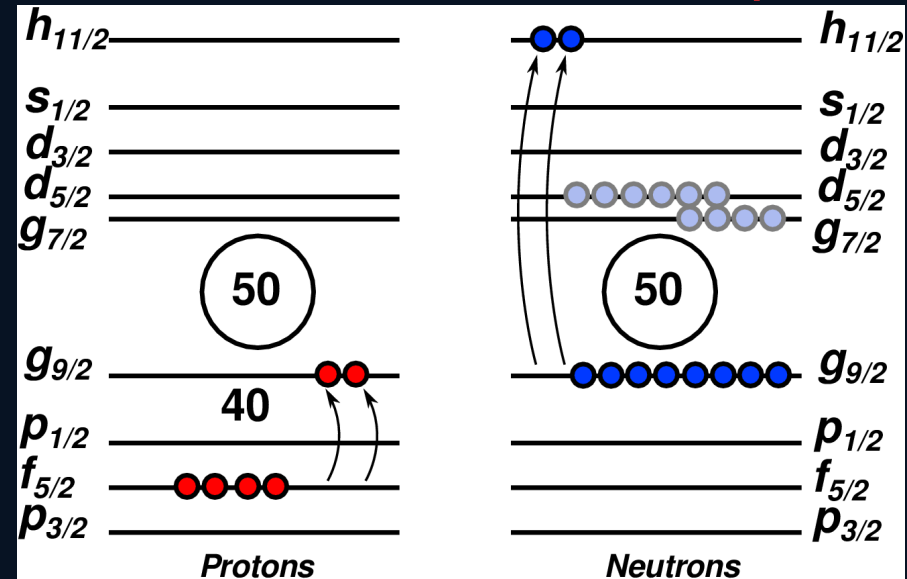
Naimi et al. PRL 105, 032502 (2010)

# Microscopic description

## Sr (Z=38) and Zr (Z=100)

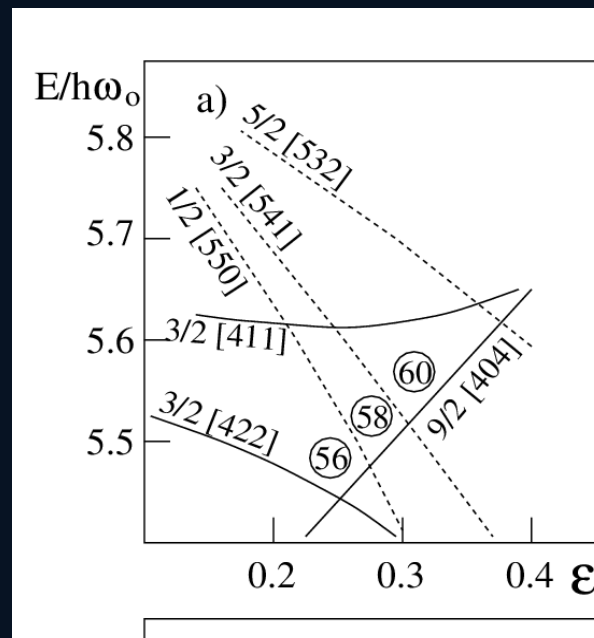
Strong correlations between the intruder proton  $g_{9/2}$  and the neutron  $h_{11/2}$  orbitals brings deformation in **Zr** and **Sr** at N=60.

### Prolate minimum deformation $\beta=0.4$



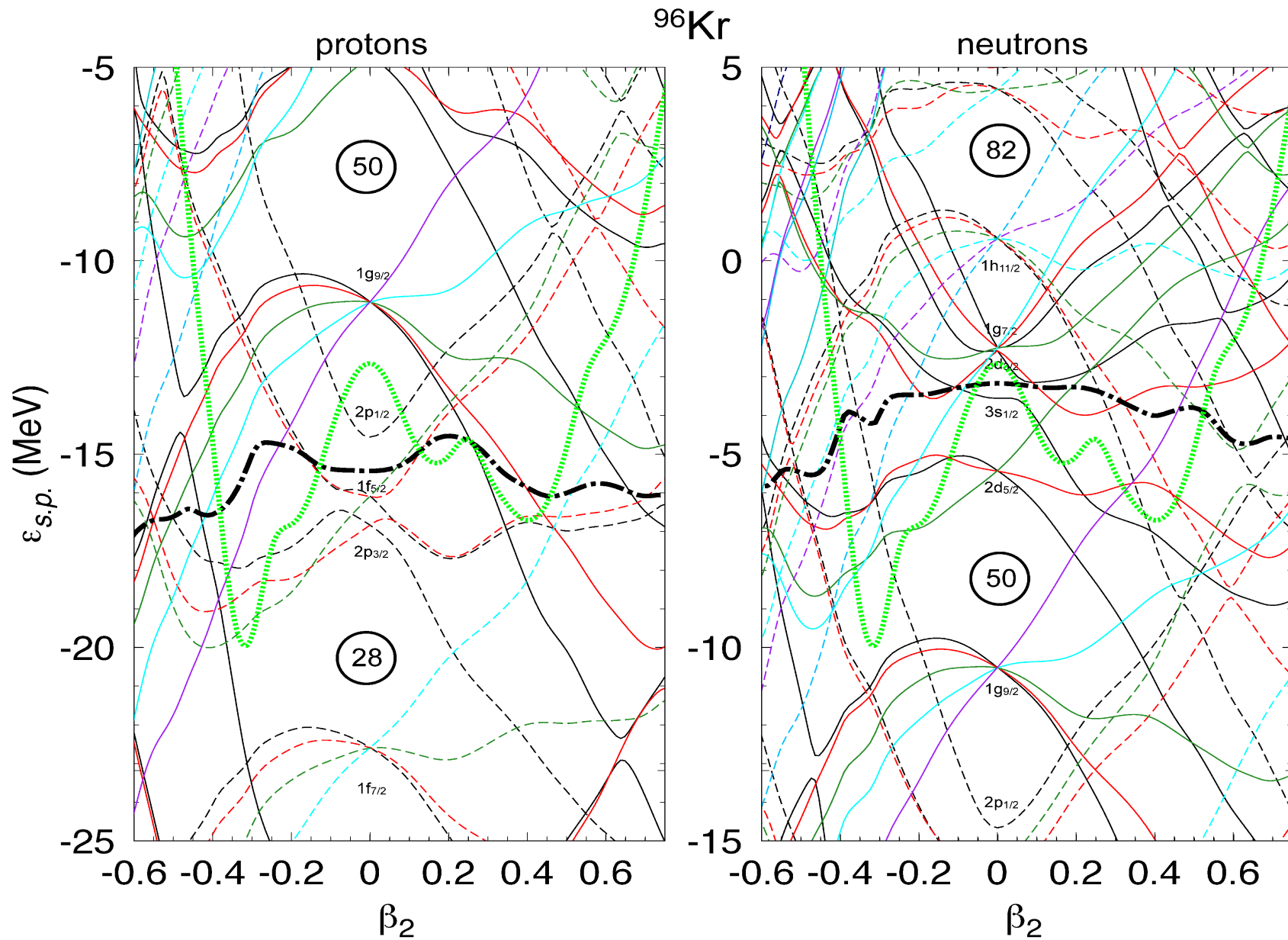
## Kr (Z=36)

The occupation of the proton  $g_{9/2}$  orbital is not enough to bring such rapid change in deformation to the system.

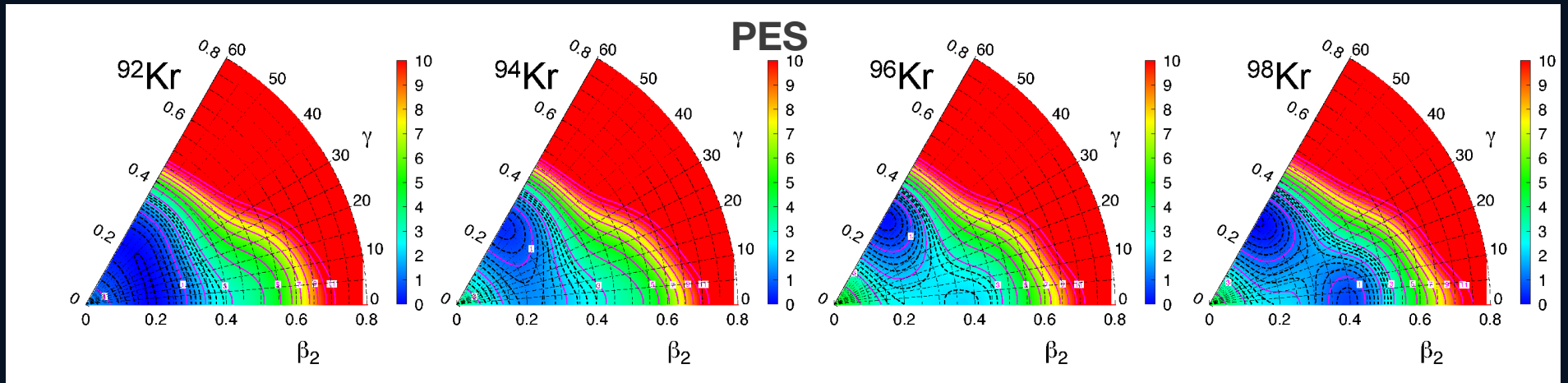


Neutron  
Nilsson  
orbitals

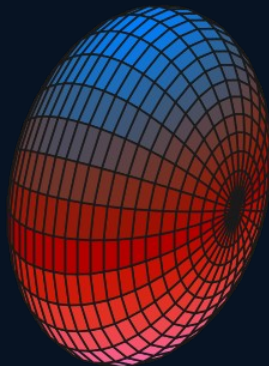
# Deformed minimums on PES



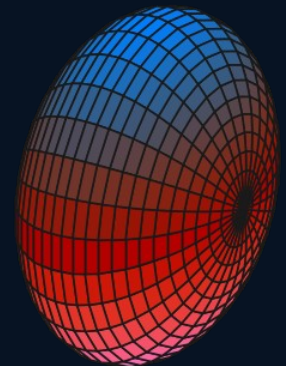
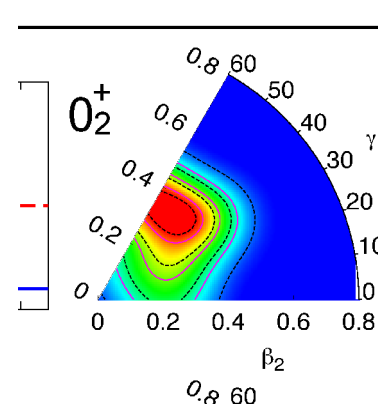
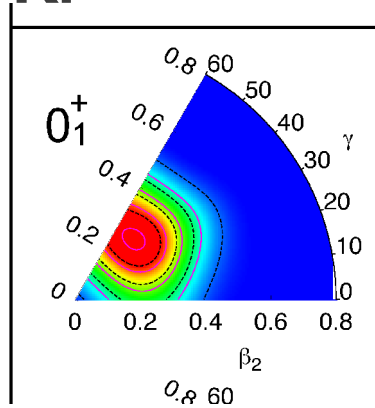
# Shapes in Kr



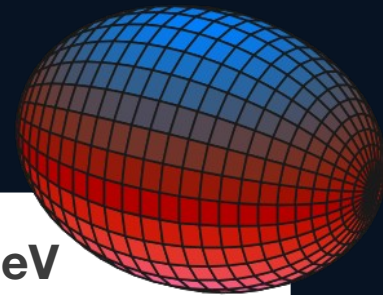
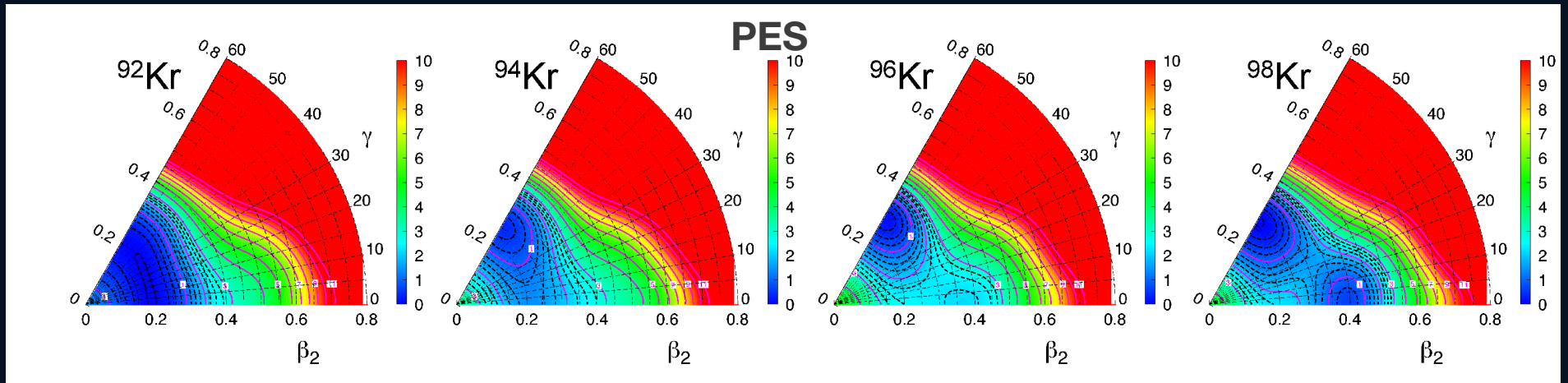
**Oblate shape  
predominance**



**94Kr**



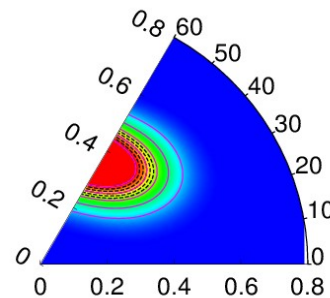
# Shapes in Kr



Shape transition through 3 different minima.

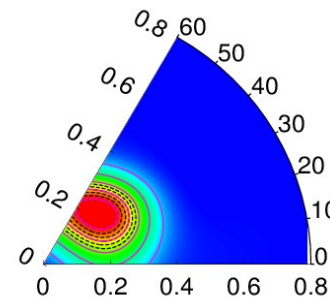
TWO oblate minima dominate the low energy spectra.

96Kr



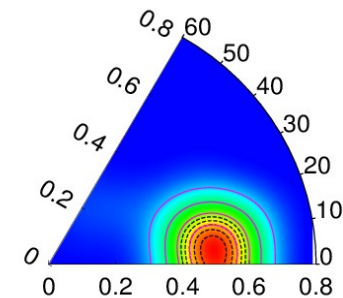
0+

1.41 MeV



0+<sub>2</sub>

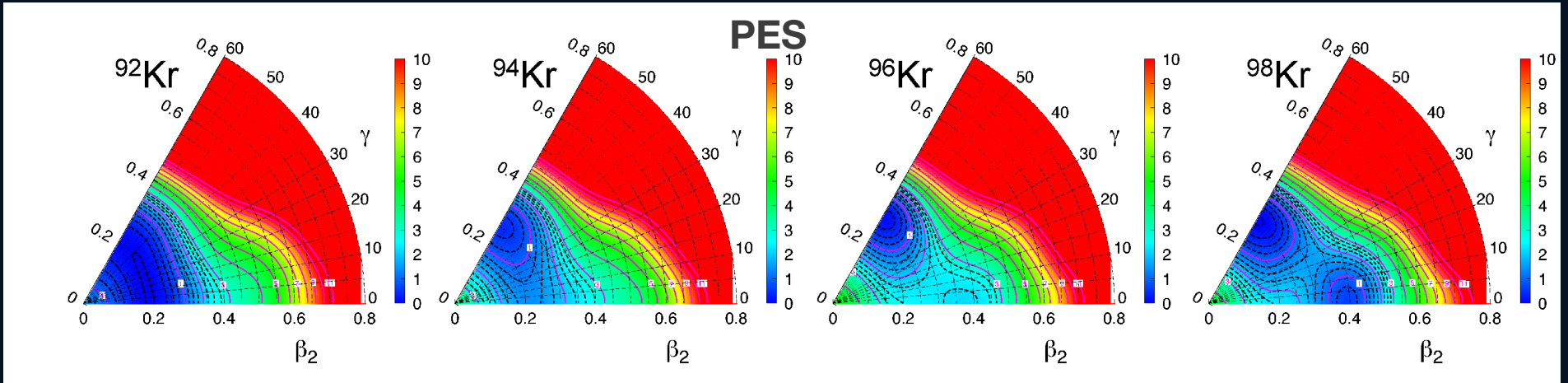
1.99 MeV



0+<sub>3</sub>

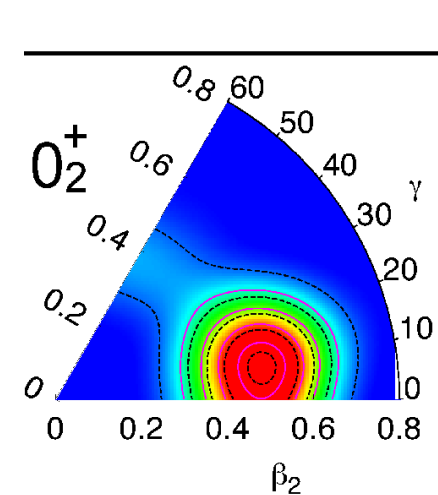
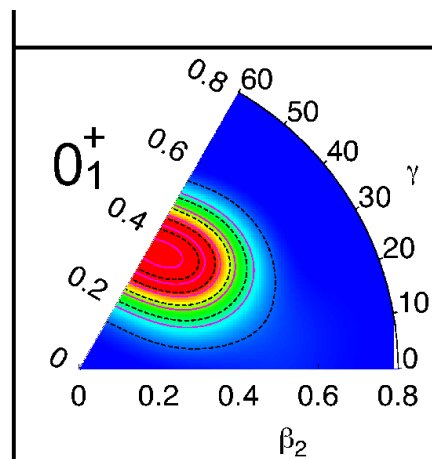


# Shapes in Kr



Shape transition to prolate shape on the second  $0_+$ , at  $N=62$

98Kr



# Coulex @ SPES

**Coulex experiment with  
MINIBALL**

**REX-ISOLDE intensities  
at the secondary target**

*Albers et al. PRL 108, 062701 (2012)*

Isotope	Year	$I_{\text{Kr}}$ [pps]	$E_{\text{Kr}}$ [MeV]	$t_{\text{Exp}}$ [s]	$R_{\text{Kr/Rb}}$
$^{94}\text{Kr}$	2009	$8 \times 10^4$	267.9	60 480	75(6)/25(3)
	2010	$4 \times 10^5$	267.9	43 560	74(7)/26(4)
$^{96}\text{Kr}$	2009	$4 \times 10^3$	273.6	32 760	43(4)/57(6)
	2010	$7 \times 10^3$	273.6	59 400	46(7)/54(8)
	2011	$<5 \times 10^2$	273.6		

**SPES**

**Estimated intensities of  
the Re-accelerated RIBs**

**C.B. eff=3- 4 %**

**Linac tr.=50%**

Element	A	Z	N	T1/2 s	RIBs at 260KeV 1+	Re-accelerated RIBs C.B. eff=3- 4 % Linac tr.=50%	q+	Max E/A
Kr	85	36	49	3.39E+08	5,93E+08	1,19E+07	15	11,8
Kr	87	36	51	4.58E+03	2,97E+09	5,94E+07	15	11,6
Kr	88	36	52	1.02E+04	4,04E+09	8,08E+07	15	11,4
Kr	89	36	53	1.89E+02	3,99E+09	7,98E+07	15	11,2
Kr	90	36	54	3.23E+01	4,37E+09	8,74E+07	15	11,2
Kr	91	36	55	8.57E+00	2,12E+09	4,24E+07	15	11
Kr	92	36	56	1.84E+00	6,89E+08	1,38E+07	15	11
Kr	93	36	57	1.29E+00	2,28E+08	4,57E+06	15	10,8
Kr	94	36	58	2.00E-01	2,49E+07	4,99E+05	15	10,8
Kr	95	36	59	7.80E-01	1,14E+07	2,29E+05	15	10,6
Kr	96	36	60	3.20E-01	1,47E+06	2,94E+04	15	10,6
Kr	97	36	61	3.17E-01	4,84E+04	9,69E+02		

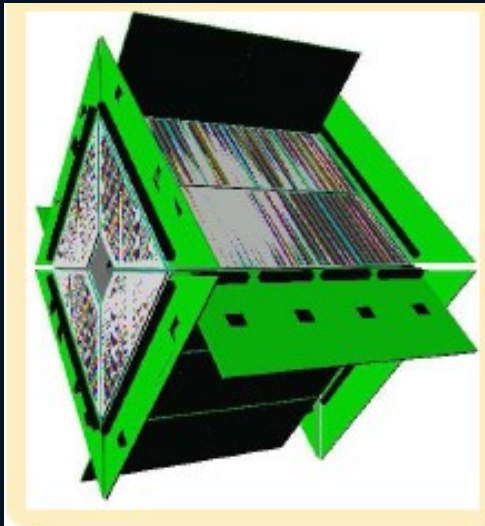
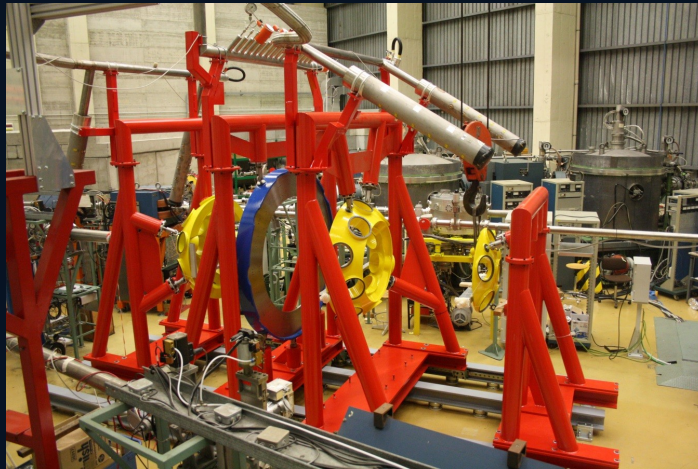
# Experimental Setup

Safe Coulex experiment with thin Pt/Au secondary target

High efficiency gamma-array

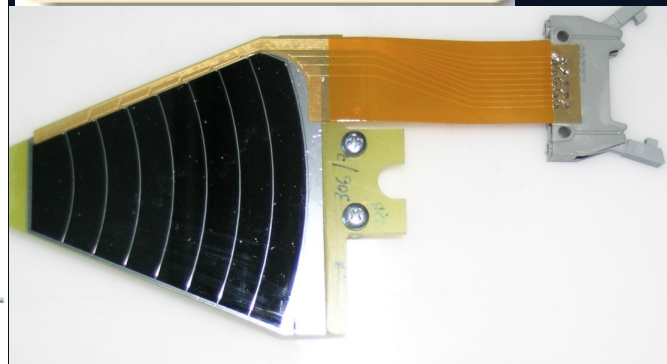
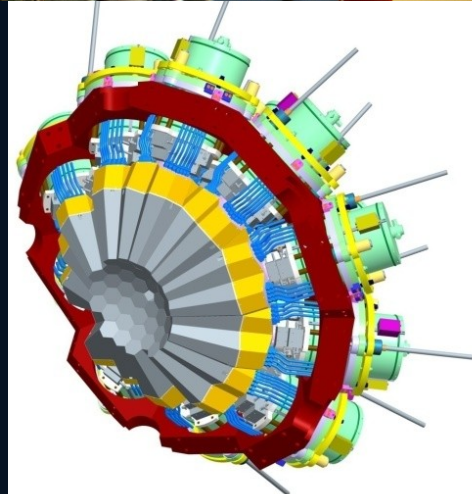
Si detectors for ion detection

GALILEO



TRACE

AGATA



SPIDER

# Experimental Setup

Additional ancillary detectors

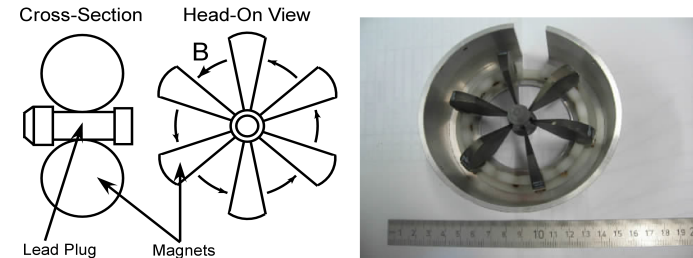
Gas filled  $\Delta E-E$  (Beam composition)

MINI-ORANGE device (Conversion electron  $E_0$  strengths)

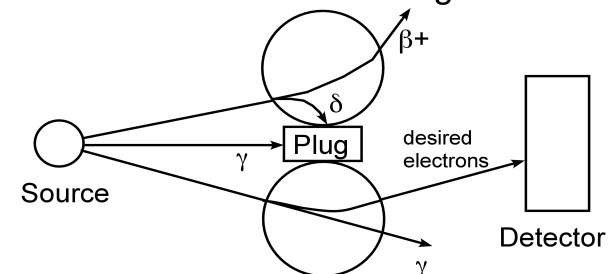
Some gamma-ray detector @ beamdump

## The Mini-Orange Spectrometer (MOS)

- Several permanent magnets surrounding a central lead plug
- Head-on view resembles segments of an orange
- Creates a toroidal magnetic field

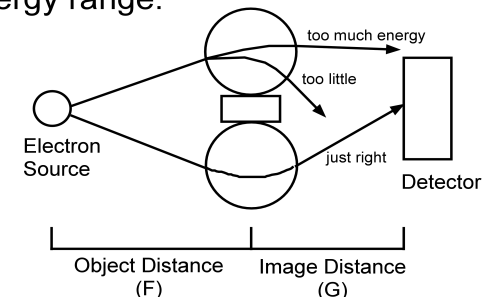


MOS removes unwanted background.



The MOS can reveal conversion electrons that would be drowned out by gammas.

MOS focuses electrons within characteristic energy range.



The MOS acts as a lens between the source and the detector

# Summary

- **Safe Coulex with a RIB delivered by SPES will lead to populate the low-lying states in  $^{96}\text{Kr}$  and obtain transition strengths.**
- **Population of the first  $0^+$  excited state: better understanding of the shape transition around  $N=60$  in the Kr chain.**
- **Also, better understanding of the shape transition at  $N=60$  for the Zr and Sr isotopes.**
- **Perfect playground for mean-field calculations.**

# Collaborators

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# Possible shape mixing

